Process Studies At The Air-Sea Interface

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LONG-TERM GOALS

To develop improved understanding and prediction of the atmosphere, with particular emphasis on severe weather. A special emphasis is placed on coastal zones and observing-system research.

OBJECTIVES

To investigate the nature of interactions at the air-sea interface under high surface wind conditions and the impact of severe weather on the coastal zone.

APPROACH

Our research approach is focussed on two aspects: investigations of the basic processes associated with spray, rainfall and high winds in the oceanic boundary layer and developing improved methods of defining and coping with the impacts of high severe weather on the coastal zone.

The oceanic boundary layer work combines basic research with direct observations using instrumented towers. The coastal impacts work started with an investigation of east-coast lows, the hybrid baroclinic systems that develop in coastal regions and bring heavy rain and snow, and high winds to coastal communities. The initial effort has evolved substantially into a major program involving coastal communities and industries affected by tropical cyclones, called the Tropical Cyclone Coastal Impacts Program, which is developing new techniques for surge and wind field analysis and forecasting, together with community response and evacuation approaches. The concept of a TCCIP has recently been adopted by both the USWRP and the Wold Weather research Program of the WMO Commission for Atmospheric Sciences and our approach will accordingly evolve into a strong international effort.

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WORK COMPLETED

We have established the boundary layer observing site at Northwest Cape in Australia to provide detailed insitu observations of tropical cyclones and general tropical weather systems up to 250 m altitude. The initial instrumentation of the Northwest Cape communication tower site has been operational for one full year. This consisted of five instrument sets on each of two 302 m towers (Fig. 1), together with a Bureau of Meteorology radar and a Doppler profiler with RASS on loan from the NOAA ETL. In late 1997 we installed four sonic anemometers on one tower to provide flux information and we expect to install our own Doppler profiler in late 1998.

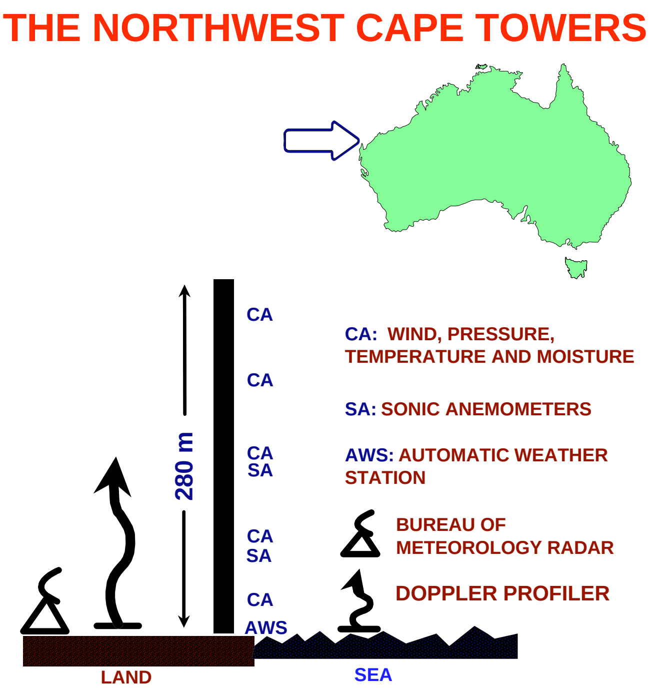

Figure 1. Schematic showing the location and basic instrument set for the Northwest Cape Instrumented Towers. Two towers right on the coast are instrumented as shown.

We have developed a new technique for obtaining accurate climatologies of east coast cyclones using available surface observing sites (Hopkins and Holland 1996), and shown that the number of cyclones on the Australian east coast had increased significantly over the past several decades. The implications for climate change have been reported to the IPCC (Hopkins and Holland 1995). We have shown that the development of an east coast cyclone follows three stages. At first a jet streak moves across the land mass and develops a tropopause fold in the left entrance region for the southern hemisphere. This fold separates to form a potential vorticity anomaly, often referred to as a cut off low. The potential vorticity is next advected underneath the jet streak and poleward towards the surface along the sloping isentropes, an essentially adiabatic process. As the anomaly approaches the strong low-level potential temperature gradients along the east coast, moist convection develops and produces a flux of potential vorticity to the surface to form the east coast cyclone. Thus, a process that commences in the upper atmosphere over the continent ultimately leads to a system that is sustained by air-sea interaction in the coastal zone. The east coast cyclone work was completed during 1998.

Development of our 3-D, diagnostic boundary layer model (Wang et al. 1997) has been essentially completed. The model consists of our full primitive equations model run at very high vertical resolution in the boundary layer and driven from above by an imposed pressure and wind field, which can be defined to evolve with time. This provides us with a tool to investigate the fine-scale structure of tropical cyclone boundary layer, its transition at landfall, and the effect of complex terrain in the coastal. Future work will be to add our spray parameterisation (Fairall et al. 1995).

Our investigation of the dynamics and uncertainties in storm surge modelling has lead to a final approach to defining a maximum envelope of waters for use in evacuation and cyclone impact mitigation work. This component of the project is now completed.

We have developed a new method for estimating the maximum potential intensity of tropical cyclones and used this to describe some of the fundamental processes involved. (Holland 1997). The approach requires only an atmospheric temperature sounding, together with surface pressure and temperature representative of the cyclone environment. It explicitly incorporates a cloudy eye wall and a subsiding eye, requires no information on trajectories of air parcels into the cyclone centre, and includes the oceanic feedback of increasing moist enthalpy associated with falling surface pressure over a steady SST. Analytic solutions exist for all known atmospheric conditions.

The derived MPI is highly sensitive to the surface relative humidity under the eye wall, to the height of the warm core, and to transient changes of ocean surface temperature. The role of the ocean is to initially contribute to the establishment of the ambient environment required for cyclone development, then to provide the additional energy required for development of an intense cyclone, which occurs as a feedback cycle where falling surface pressures enable release of more energy from the ocean. The major limiting factor on cyclone intensity is the height and amplitude of the warm core that can develop, which is defined by the height to which eye-wall clouds can reach. We have shown that much of the upper-level warming associated with tropical intensification arises directly from moist processes. Compressional warming in the eye is of significance only mid levels.

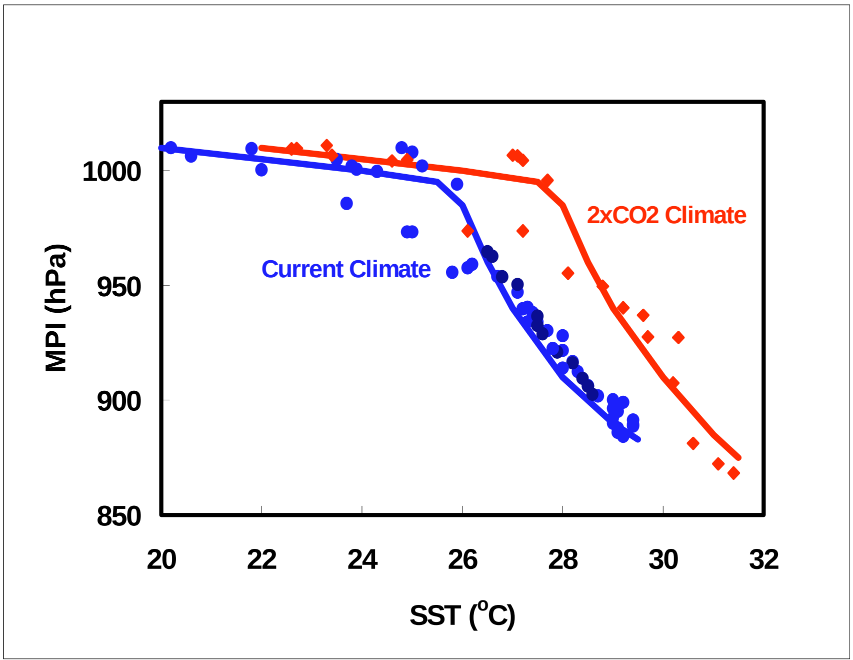

Figure 2: Thermodynamically derived relationship between SST and maximum potential intensity for current climate and a doubling of atmospheric CO_2. Points show the scatter in individual observations (blue circles) or model soundings (red diamonds).

Application of the method to a cyclone case study and empirical MPI relationships indicates very close agreement (e.g. the blue curve in Fig. 2). For SST$\leq$26^{o}C, the level of neutral equilibrium for moist uplift of surface air is below the 250 hPa level for all soundings examined in this study. Insufficient warming and hydrostatic pressure falls can therefore be achieved to start the cyclone intensification process. We suggest that this lack of available thermodynamic energy is the primary reason why cyclone development is constrained to regions of SST>26^{o}C in the absence of unusual transients or baroclinic processes.

The thermodynamic method has been applied to estimates of climate change (Fig. 2; Henderson-Sellers et al. 1997, Tonkin et al. 1997). This work, which was commissioned by the WMO Commission for Atmospheric Sciences, indicates that tropical cyclones can be expected to increase in intensity with projected global climate change due to anthropogenic effects. Indicative increases are for up to 10% in the maximum winds, which is modest and well within the natural variability that is currently experienced across ocean basins. Caution is applied to the results, however, as we have not yet fully included the effects of surface interactions associated with spray.

RESULTS

Low Level Jets in the Tropical Cyclone Boundary Layer: We have used our high resolution tropical cyclone boundary layer model to show that the low level wind maximum often observed at around 500 m can be produced by strong inwards advection of angular momentum in the inflowing air. Moreover, we have shown that the wind speed within the jet is supergradient to the order of 10%. This imbalance would normally be expected to weaken (or reverse) the inflow and eliminate the supergradient flow by a geostrophic adjustment mechanism. However, the inflow at the jet level is maintained against this "centrifuging out" largely by vertical advection, with horizontal advection and vertical diffusion playing a smaller role.

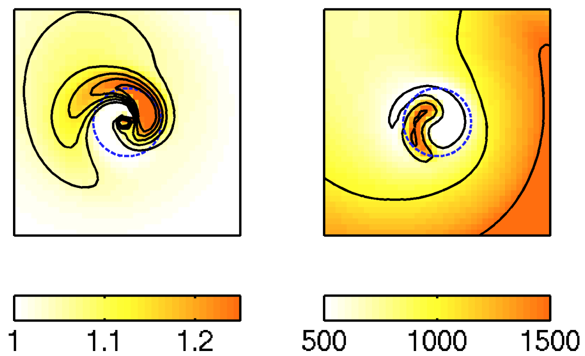

Figure 3: Jet strength (relative to the gradient wind speed) and height for a tropical cyclone with central pressure 960 hPa translating towards the east at 5 $m.s^{-1}$. Contour intervals are 0.05 (left) and 500 m (right).

We further showed that the strength and distribution of the jet depended upon the radial wind profile and the movement of the storm, and on the environment in which it was embedded. In an inertially neutral storm, with a peaked wind profile, the jet is concentrated near the eyewall, while in a less peaked storm, it is weaker but more widely distributed. For a moving storm, the most supergradient winds were found to be on the weaker side of the storm (Fig 3).

By demonstrating that horizontal advection plays a major role in determining boundary layer winds, we have invalidated the theoretical foundation for the one-dimensional models widely used to "reduce" flight or gradient level winds to the surface. Surface wind reduction factors were calculated and found to vary from 0.7 to almost 1 within a single, moving storm. Fortunately, the larger values occur on the weaker side of the storm. This may partly explain the relatively poor performance of profile models in tropical cyclones, and the wide variation in published surface wind reduction factors.

This work is the first project using our high resolution boundary layer model. Future stages will investigate processes determining the horizontal distribution of the wind field, the impact of changes at landfall (including orography) and the impact of sea spray evaporation. These will input into our enhanced parametric wind field model.

Parametric Windfield Model: We have begun work on an improved parametric wind field model suitable for risk prediction and bogussing work, as well as input into oceanic models. It follows from a recommendation of the recent IWTC, and is expected to feed into the WWRP/USWRP/TCCIP forecast demonstration project on the tropical cyclone wind field at landfall. Progress to date has focused on improving the specification of the outer wind field. Future work will include the development of a parameterisation of the surface wind reduction which includes the effects of the radial wind profile and environment outlined above.

Sea Spray Evaporation: We have used our column boundary layer model with explicit evaporation and transport of sea spray droplets to identify and quantify the processes which limit the droplet-mediated latent flux. These include a variety of negative feedbacks, the most significant of which was shown to result in about 70% of the water evaporated from droplets being transported above the droplet evaporation layer under typical tropical cyclone conditions. We found also that the evaporation layer was several tens of metres deep, for droplets near the peak production radius. Work commenced on an evaluation of the droplet production rate under various conditions, which is now the major uncertainty in determining the impact of spray evaporation on weather systems. This work was carried out in collaboration with Chris Fairall of NOAA/ETL.

Use of MPI for Actual Cyclone Intensity Change: We have commenced an investigation of the relationship between thermodynamic limits and the actual maximum intensity achieved by individual tropical cyclones. Tonkin et al. (1999) has shown that cyclones in the Coral Sea region east of Australia can be broken into two classes: those that do or do not reach hurricane force. The intensity of the weaker cyclones does not have any relationship to the thermodynamic limit, indicating that other processes have operated to inhibit intensification. Modelling studies are being undertaken to investigate the inhibiting factors. However, intense cyclones seem to normally approach the local thermodynamic limit in all cases. This limit can be substantially modified from the regularly used monthly mean. Such modifications occur in both the atmosphere and the ocean and always seem to work to reduce the MPI. The physical basis of this finding is being further investigated.

IMPACT/APPLICATIONS

Our strategic research is geared towards developing improved understanding and new methodologies and techniques for forecast application. We have provided regular seminars and discussions with staff at operational centers, including JTWC, and we are involving forecasters, engineers and community people in workshops aimed at defining the major operational problems. The Tropical Cyclone Coastal Impacts Program is designed to develop advanced methods from the latest research for direct use in forecasting and community response approaches.

TRANSITIONS

The maximum envelope of waters approach to storm-surge forecasting has been completed for three basins in a trial mode and has now moved into operations. The technique has now been established in a mode suitable for application to other ocean basins and this is available to all interested groups. The code for using the thermodynamic method to obtain maximum potential intensity estimates has been provided to a number of organizations, including GFDL, and is freely available on request. This method is straightforward to apply and is applicable to actual soundings or to operational analyses, numerical model forecasts and climate model simulations.

RELATED PROJECTS

We are working with the USWRP and the WWRP on defining plans for the new international initiative on landfalling tropical cyclones. We also have commenced a collaboration with the University of Rhode Island (Isaac Ginis) on investigating processes at the air-sea interface under high wind conditions. Observations from the observing site at Northwest Cape are being provided for operational use and we welcome collaboration on the related research.

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A selection of references is provided. Full information may be obtained at our web site. Information on the Tropical Cyclone Coastal Impacts Project is at: http://www.bom.gov.au/bmrc/meso/Project/TCCIP/tccip.html

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